REPORT TO CONGRESS
ON
THE RESTRUCTURING OF THE EARTH OBSERVING SYSTEM

SUBMITTED TO:
COMMITTEES ON APPROPRIATIONS
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Submitted by:

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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THE RESTRUCTURING OF THE EARTH OBSERVING SYSTEM

The following is a report to the Congress on the restructuring of the Earth Observing System program, the centerpiece of NASA's Mission to Planet Earth. This report is submitted pursuant to the requirements stated in the Conference Report accompanying HR 2519, the VA, HUD, Independent Agencies Appropriations.

The Earth Observing System (EOS) is designed to provide comprehensive, long-term observations from space of changes that are occurring on the Earth from natural and human causes so that we can have a sound scientific basis for policy decisions to protect our future. EOS will provide the continuation and extension of observations of the Earth that are now being undertaken as part of Mission to Planet Earth.

As is directed by the Committees on Appropriations, EOS is being restructured for three principal reasons:

> To focus the science objectives of EOS on the most important problem of global change -- global climate change.
>
> To increase the resilience and flexibility of EOS by flying the instruments on multiple smaller platforms rather than a series of large platforms.
>
> To reduce the cost of EOS, including spacecraft, instruments, data system and science, from $16 billion to $11 billion through FY 2000.

The process by which NASA has restructured EOS to meet these constraints has been thorough, involving reviews by an external committee, evaluation by the scientists who will use the EOS data, and systematic engineering studies of spacecraft configurations and launch options. In July 1991 NASA presented the constraints to the EOS Engineering Review Committee chaired by Dr. E. Frieman (the Frieman Committee), and discussed with them options for how the EOS spacecraft could be reconfigured. The Frieman Committee in its report endorsed these options as a "proof of concept" for an EOS which contains a "favorable measure of resiliency." In August 1991 NASA discussed payload options at the Seattle meeting of the Investigator Working Group of all EOS investigators, and in October, conducted a formal review by the EOS Payload Advisory Panel. This committee is comprised of the EOS interdisciplinary investigators and is formally charged with recommending EOS payloads to NASA. Concurrently, extensive engineering studies were conducted by the Goddard Space Flight Center to determine the most effective spacecraft configuration so that the instruments can be accommodated on smaller platforms. In December 1991 the NASA Administrator conducted a thorough review of and approved the restructured EOS program.

The final payload configurations for the restructured EOS satisfy the Congressional constraints -- they focus on climate change, are launched on multiple smaller platforms, and have a total cost of $11 billion through FY 2000. The final payloads are very similar to those endorsed by the Frieman Committee and wholly consistent with the Committee's recommendations. These payloads satisfy the recommendations of

the EOS Payload Advisory Panel with the caveat that some of the instruments will fly later than recommended due to the constraints on the budget.

The National Space Council, chaired by the Vice President, is currently developing a National Space Policy Directive covering the space-based elements of the U.S. Global Change Research Program. This document will direct NASA to implement the restructured EOS program as part of an overall space-based global change observation system.

1. THE SCIENCE OBJECTIVES OF EOS: The purpose of the restructured Earth Observing System, is to determine the extent, causes, and regional consequences of global climate change. The extent -- the change in average temperature and the time scale over which it will occur -- is presently unknown. The causes can be either natural or human induced. It is the latter, however, that must be understood if we are to alter human behavior and avoid the climate changes which are most detrimental. The regional consequences -- changes in precipitation patterns, length of growing seasons, severity of storms, sea level, etc. -- must be understood if we are to determine which aspects of climate change will be detrimental and how we should adapt to those changes which cannot be avoided.

The behavior and evolution of the climate system is determined by complex processes within and interactions among the atmosphere, the oceans, the biology, and the snow and ice systems of the Earth. Scientists and policy-makers have documented in recent years which of these processes and interactions are most important to understand. In particular, the Intergovernmental Panel on Climate Change, the scientific priorities of the US Global Change Research Program, and the EPA report "Policy Options for Stabilizing Global Climate" are all in agreement that if we are to understand the climate and what the human species is doing to it, we must develop a quantitative understanding of seven key issues:

The Role of Clouds, Radiation, Water Vapor, and Precipitation.

The Productivity of the Oceans, their Circulation, and Air-Sea Exchange.

The Sources and Sinks of Greenhouse Gases, and their Atmospheric Transformations.

Changes in Land Use, Land Cover, Primary Productivity, and the Water Cycle.

The Role of the Polar Ice Sheets, and Sea Level.

The Coupling of Ozone Chemistry with Climate and the Biosphere.

The Role of Volcanoes in Climate Change.

The instruments that will fly in the restructured EOS program have been selected to address these key scientific issues associated with climate change. The original EOS program addressed a broader range of global change issues, including studies of stratospheric chemistry and its controlling influence on ozone depletion, and aspects of solid Earth physics. The original EOS program included a total of 30 selected instruments. By focusing on climate change, the required instruments are reduced to 17 that need to fly before 2002; 6 that are deferred, and 7 that are deselected.

2. NEW SPACECRAFT CONFIGURATIONS: In the original EOS program the instruments were to be flown on a series of large platforms, each containing about 15 instruments and launched on a Titan-IV with solid motor upgrades. There are certain advantages to the large platform approach:

(i) The total cost for flying a set instruments on a large platform is less than the total cost of flying that same set of instruments on multiple smaller platforms.

(ii) It is easier on a large platform to accommodate those instruments which need to make simultaneous observations of the Earth. The sensitivity of the EOS instruments is such that they generally rely on simultaneous measurements from other instruments, through the same column of air, in order to make atmospheric corrections and/or to pursue their science objectives.

However, there are also major disadvantages to the large platform approach:

(i) The large platform with multiple expensive instruments is inflexible to budget shortfalls or overruns. The only solution to budget problems is to slip the launch of the platform and all its instruments, thereby delaying the acquisition of EOS data.

(ii) The large platform with multiple instruments is inflexible to technical problems. If one major instrument experiences development delays, the launch of the entire platform will slip.

(iii) The orbit of a large platform cannot be optimized for each of the multiple instruments it will carry. Instruments can have different requirements for orbital altitude and inclination and for the time of day at which the spacecraft crosses over points on the Earth.

(iv) A launch failure, which is the greatest single risk to space missions, will result in a greater catastrophic loss to a large platform mission than to smaller platform missions.

When the EOS program was designed, prior to FY 1991, the only available launch vehicle for EOS spacecraft was a Titan-IV. EOS spacecraft are launched from the

Western Test Range at Vandenberg Air Force Base in California into sun-synchronous, polar orbit. Such orbits provide both global coverage and allow the spacecraft to pass over points on the Earth at the same time each day, and thus observe with constant sunlight conditions. The launch vehicles available from the west coast were expected to be only a Delta-class, which is too small to accommodate most of the required payload configurations for EOS, or the large Titan-IV-class, which can easily accommodate the large platform, with 15 instruments. Accordingly, EOS was designed in the large platform configuration.

In the spring of 1991, the Air Force announced that it would seek funds to construct facilities at Vandenberg to launch intermediate launch vehicles, in the Atlas IIAS-class. Such vehicles can accommodate payloads which are approximately one-third those of the Titan-IV, and which are large enough to include appropriate groupings of EOS instruments. Thus it is now possible, whereas it was not earlier, to reconfigure the EOS payloads to fly on multiple smaller platforms.

The Frieman Committee, and most of the other advisers that NASA has consulted on EOS, advocated that it is appropriate to fly the EOS instruments on multiple platforms. This approach has advantages which are the reverse of the disadvantages of the large platform approach. It is flexible in being able to accommodate budget shortfalls and overruns, as well as technical difficulties. The optimum orbits can be chosen for each of the instruments. Finally, it is more resilient to catastrophic loss from a single launch failure.

NASA, with input from the Frieman Committee, and detailed recommendations from the EOS Payload Advisory Panel, has reconfigured EOS to fly the 17 instruments required for global climate change studies on (i) three intermediate spacecraft that can be launched on Atlas IIAS-class vehicles, (ii) one smaller spacecraft to be launched on a Delta-class vehicle, and (iii) two small spacecraft to be launched on Pegasus-class vehicles. The names of the spacecraft, their launch dates and vehicles, and their purposes are as follows:

EOS-AM (June 1998, Atlas IIAS-class) -- Characterization of the terrestrial surface; clouds, aerosols and radiation balance.

COLOR (1998, Pegasus-class) -- Oceanic biomass and productivity.

AERO (2000,Pegasus-class) -- Atmospheric aerosols.

EOS-PM (2000, Atlas IIAS-class) -- Clouds, precipitation, and radiative balance; terrestrial snow and sea ice; sea-surface temperature and ocean productivity.

ALT (2002, Delta-class) -- Ocean circulation and ice sheet mass balance.

CHEM (2002, Atlas IIAS-class) -- Atmospheric chemical species and their

transformations; ocean surface stress.

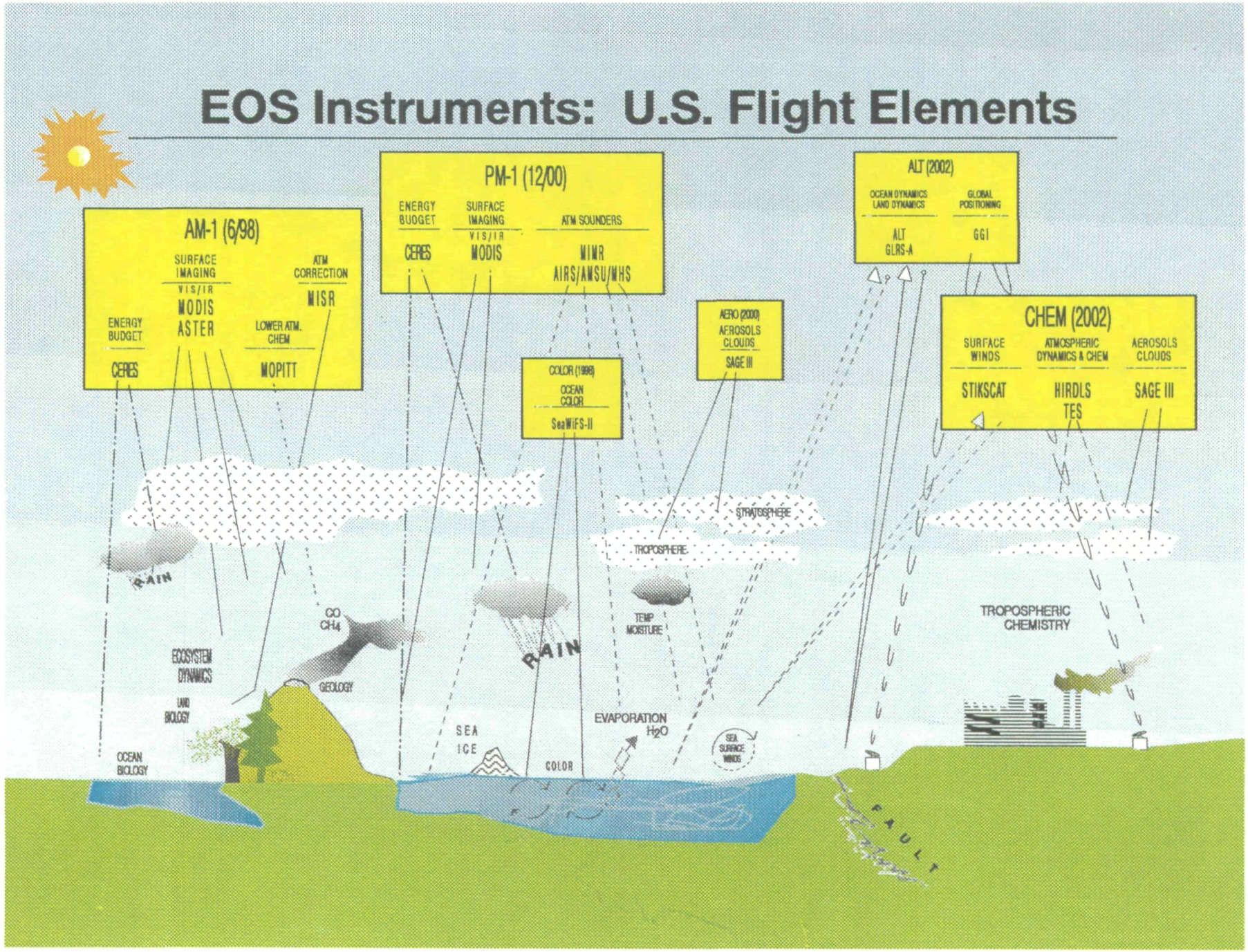
The instrument configurations and the observations they will make are shown pictorially in Figure 1. (The acronym for each of the instruments is defined in the Appendix to this report.) The impact of these missions on our understanding of the climate system of the Earth is discussed in the next section.

The orbits for EOS-AM and EOS-PM are both sun-synchronous, polar, but with different crossing times. The EOS-AM spacecraft primarily observes surface features and thus prefers a morning crossing time when cloud cover is a minimum. In contrast, EOS-PM includes an instrument which is a candidate, next-generation atmospheric sounder for deployment on future NOAA operational satellites. It prefers an afternoon crossing time which is most useful for contributing data for meteorological forecasting. Moreover, both EOS-AM and EOS-PM observe characteristics of the terrestrial surface and of the atmosphere. By having measurements at two different times of the day it is possible to study diurnal variations in these features. The orbits for COLOR, ALT, and CHEM are also sun-synchronous, polar, but the optimum orbit for AERO is 57 degree inclination.

As can be seen in Figure 1, certain instruments are flown on more than one spacecraft. The MODIS-N instrument, which is a moderate resolution spectrometer capable of observing both the surface and the atmosphere, is included on both EOS-AM and EOS-PM because MODIS-N has critical simultaneity requirements with the other instruments on each of these spacecraft. That is, the observations from MODIS-N seen simultaneously through the same column of air are required to interpret the data from these other instruments. By including MODIS-N on each of these spacecraft it is unnecessary to do complicated formation flying, and the EOS-AM and EOS-PM spacecraft can each be flown in its optimum orbit. Moreover, MODIS-N is the central instrument on EOS, and with it flying on two separate spacecraft the program has important redundancy. The CERES instrument, which measures the energy budget of the Earth, is flown on both EOS-AM and EOS-PM to give measurements at two different times of the day. The SAGE-III instrument, which measures atmospheric aerosols, is flown on AERO and CHEM to provide measurements from two different orbits, 57-degree inclination and polar, respectively.

The launch of the EOS-AM spacecraft is in June 1998, six months earlier than the planned launch of the first large platform in the original EOS program. By reducing the size of the payload it is possible to launch earlier. The launch dates of the remaining EOS spacecraft will occur over the next four years, through the year 2002. Every effort will be made to hold the launch date of EOS-AM in June 1998, and then EOS-PM in 2000. The program has flexibility in that limited budget shortfalls or overruns can be accommodated by minor slips in the launch dates of the COLOR, AERO, ALT and/or CHEM spacecraft.

EOS is to be a long-term program, providing continuous observations of the causes of global climate change. The principal EOS spacecraft, EOS-AM, EOS-PM, etc., will


EOS Instruments: U.S. Flight Elements
AM-1 (6/98)
SURFACE IMAGING
VIS/IR
MODIS
ASTER
ATM CORRECTION
MISR
ENERGY BUDGET
CERES
LOWER ATM. CHEM
MOPITT
PM-1 (12/00)
ENERGY BUDGET
CERES
SURFACE IMAGING
VIS/IR
MODIS
ATM SOUNDERS
MIMR
AIRS/AMSU/MHS
COLOR (1998)
OCEAN COLOR
SeaWiFS-II
AERO (2000)
AEROSOLS
CLOUDS
SAGE III
ALT (2002)
OCEAN DYNAMICS
LAND DYNAMICS
ALT
GLRS-A
GLOBAL POSITIONING
GGI
CHEM (2002)
SURFACE WINDS
STIKSCAT
ATMOSPHERIC DYNAMICS & CHEM
HIRDLS
TES
AEROSOLS
CLOUDS
SAGE III
STRATOSPHERE
TROPOSPHERE
RAIN
CO
CH4
ECOSYSTEM DYNAMICS
LAND BIOLOGY
GEOLOGY
OCEAN BIOLOGY
SEA ICE
RAIN
TEMP MOISTURE
EVAPORATION
H2O
COLOR
SEA SURFACE WINDS
TROPOSPHERIC CHEMISTRY
FAULT

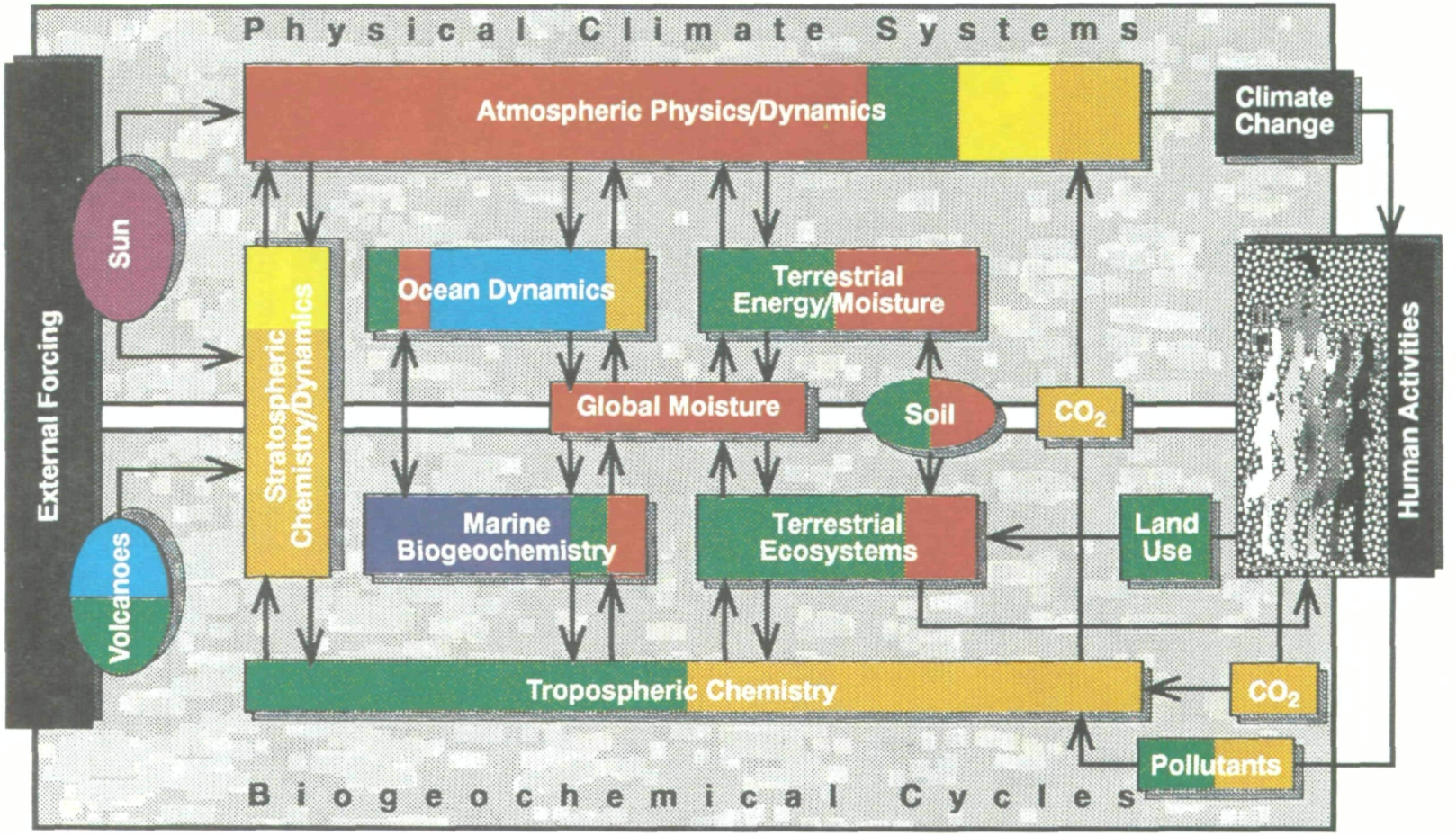
thus be repeated twice on five-year centers for at least fifteen year coverage. However, the payloads on the follow-on EOS spacecraft could change, depending on the evolution of scientific understanding of global change and the development of technology. For example, the ASTER instrument on the first EOS-AM spacecraft could be replaced by the high resolution spectrometer, HIRIS, on the second EOS-AM spacecraft. Actual decisions on instruments to fly on follow-on spacecraft do not need to be made for some years. However, technology development efforts need to continue to insure that subsequent generation instruments are available when needed.

3. THE IMPACT OF THE RESTRUCTURED EOS ON UNDERSTANDING THE CLIMATE: *Scientists agree that the climate system of the Earth is governed by a series* of interacting components which are illustrated in Figure 2. External inputs to the climate come from human activities, shown on the right of the figure, and natural inputs such as volcanoes or changes in solar output, shown on the left. The internal components of the climate system -- the components of the atmosphere, the oceans, and the biology -- are then coupled together through a series of interactions denoted by the arrows in the figure. Interactions involving primarily physical and chemical processes are included in the gray box labeled "Physical Climate System." Interactions that also involve mainly the chemical and biological processes of the Earth are included in the box labeled "Biogeochemical Systems."

Our knowledge of the individual components which govern the climate system of the Earth is represented by large-scale numerical models which should (i) include all the relevant physical, chemical, and/or biological processes that determines the behavior of each component and its interactions with other components, (ii) include comprehensive data on the current state of the component, and (iii) allow us to predict the future of the component. However, the accuracy and completeness of current models of the components of the climate system are inadequate, and also vary widely depending on the component being modeled. The lack of appropriate observational data is the principal impediment to improving models of the components and to coupling these models together into a comprehensive model of the whole climate system.

Consider a hypothetical scale for the accuracy and completeness of numerical models of the Earth in which current models for a five-day regional weather forecast are a "10". On this conceptual scale, then, current climate models that focus upon atmospheric dynamics, the so-called general circulation models (GCM's), rate approximately a "6". There is similarity in the physics that is important in five-day weather forecast models and in global atmosphere models. However, GCM's have time scales of weeks to years and are more strongly influenced by the poorly understood effects of clouds and aerosols which can cause heating or cooling of the atmosphere and surface. In addition, the couplings within the climate system, for instance between the ocean and the atmosphere, are more complex over the inherently longer time scales of the climate system.

NASA's EOS Mission Contributions to Global Climate Modeling



Integrated Model of the Earth System for Decadal Climate Prediction

ARROW KEY → = INTERACTION

On this same conceptual scale, the accuracy and completeness of current global models for ocean circulation rate approximately a "4"; global models of ocean circulation that include the calculation of marine biological activity are just now being developed. Global models of terrestrial ecosystem that treat the rate at which they exchange carbon and water with the atmosphere rate perhaps a "2" on this scale; global terrestrial ecosystem models that treat the effects of climate change and feedbacks to the climate change are also just now being developed. These models, particularly those involving the biology, suffer from lack of data to determine the relevant processes which govern their behavior, as well as from inadequate data to determine the current state of the component.

As is shown in Figure 2, the components of the climate system are coupled to each other. Thus, an adequate, comprehensive model for the climate system requires adequate and comprehensive models for each of the components, and verification of the method for coupling the components together. Even if we improve the accuracy and completeness of models of the atmosphere, their utility to predict the future of the climate is severely limited unless we also improve the accuracy and completeness of the models of both the oceans and the terrestrial components. Furthermore, the regional consequences of climate change, on sea levels and agriculture, cannot be assessed without accurate models of the oceans and the biology of the Earth. However, this does not mean that all models need to reach the highest level of sophistication or that they need to reach the same level of completeness.

It is unrealistic, and unnecessary, to attempt to develop a global atmosphere model that will provide specific forecasts on a daily basis that is analogous to five-day weather forecast models. We are, after all, looking only for changes in the climate by region, and by month or by season, on which to base policy. Thus, on our scale where weather forecast models are a "10", a realistic goal for global atmosphere models is an "8".

Our goals for models of the oceans and the biology of the Earth can be less demanding since many of the controlling processes operate on longer time scales and therefore may be treated initially by relatively simpler models. In addition, advances of 50-200 % in these less well modeled subsystems will yield significant contributions toward the development of integrated climate system models. Continuing with the simple scale concept, a realistic goal for models of both the oceans and the biology of the Earth is a "6", though the treatment of the physical circulation of the oceans will need perhaps to reach a level more consistent with the general circulation models of the global atmosphere (e.g. an "8"). Clearly, models of the terrestrial biological systems, which we currently rate as a "2", have the furthest to improve; however, initial improvements in these more data-sparse components will be relatively rapid and, as mentioned, very valuable.

The EOS spacecraft are designed to provide the observations that will allow us to make the necessary improvements in the models of the Earth's climate system, and to monitor its long-term evolution. These observations need to be supplemented with

extensive, coordinated ground and aircraft measurements, which are to be funded outside of the EOS program and in many cases by other Federal agencies or our international partners. The color-coding on the figure describing the climate system (Figure 2) indicates which of the EOS spacecraft will study each of the components. The actual observations that each of the EOS spacecraft will make, and the instruments that will make them, are shown pictorially in Figure 1 in section 2.

The EOS-AM spacecraft (shown in green in the figure describing the climate system), and its accompanying small mission COLOR (shown in blue) will provide the observations that will allow the required improvements in models of the biology of the Earth. These spacecraft will study terrestrial ecosystems, marine biogeochemistry, land use, soil, terrestrial energy/moisture, tropospheric chemistry, etc. Improvements in models of the biology require observations of the surface of the Earth and its vegetation in many different wavelengths of radiation. This quantitative information then provides the basis for understanding the processes which govern the biology. EOS-AM, in particular, is a major improvement in wavelength coverage over any mission that will precede it, and thus should provide the required improvements in models of the component of the climate system that are the least developed.

The EOS-PM spacecraft (shown in red in the figure), and its accompanying small mission AERO (shown in yellow) will provide the observations that will allow the required improvements in models of the dynamics of the atmosphere of the Earth. These spacecraft will study atmospheric physics/dynamics, global moisture, etc. The EOS-PM and AERO instruments have improved spectral resolution over preceding missions, and thus should produce the required quantitative understanding of the hydrological cycle and other aspects of the energy balance in the atmosphere.

The observations from the EOS-AM and EOS-PM spacecraft also complement each other. Spacecraft which observe the surface of the Earth in general observe the atmosphere as well, in part to make needed atmospheric corrections to their measurements. Conversely, spacecraft which observe the atmosphere can see the surface. Thus, the EOS-AM spacecraft can also observe aspects of the atmosphere, such as clouds and their effects on the Earth's radiation balance, and the EOS-PM spacecraft, aspects of the surface. These measurements come at different times of the day -- EOS-AM in the morning and EOS-PM in the afternoon -- and provide an opportunity to study variations in the atmosphere and on the surface during the daily heating and cooling cycles.

Models of the oceans of the Earth should improve in the next few years with observations of global circulation from the US/France TOPEX/Poseidon mission, which will be launched in 1992, and from observations of air-sea interactions from the Japanese ADEOS mission in 1995, which includes the flight of two US instruments. The time scales for phenomena in the oceans, however, are quite long, and thus the TOPEX/Poseidon and ADEOS missions, which are of limited duration, will not provide all the observations needed to make the required improvements in ocean models. The EOS mission will thus continue the TOPEX/Poseidon and ADEOS measurements,

at the same spatial and spectral resolution, from the ALT and CHEM spacecraft, respectively.

The chemistry of the lower atmosphere, or troposphere, is determined by emissions from the biology of the Earth and from human activities. However, the chemistry of the troposphere is difficult to study from space with current instrumentation. The CHEM spacecraft, which is the last of the first series of EOS spacecraft, is planned to carry an advanced instrument that will for the first time provide detailed measurements of the chemistry of the troposphere. These measurements will provide important information of the transformations of "greenhouse" gases in the troposphere, and an essential check on the models of the biology and atmosphere that are developed using data from earlier EOS spacecraft.

Models of ozone depletion, and the governing processes in the stratosphere, should improve substantially in the next few years with observations from the Upper Atmosphere Research Satellite (UARS). This problem is important to climate change studies in that ozone depletion in the lower stratosphere can affect the heating or cooling of the troposphere. Thus, the CHEM spacecraft, which launches essentially ten years after UARS, will also carry instruments to check the accuracy of models of stratospheric chemistry.

The launch sequence for the EOS spacecraft is determined by technical, programmatic, and scientific reasons. The scientific reasons provide a compelling logic. The first two spacecraft, EOS-AM and COLOR, will provide the data to improve the models of biology of the Earth -- the models most in need of improvement. The second two, EOS-PM and AERO, will provide the data needed to improve the models of the dynamics and energy balance of the atmosphere, which is of primary influence on the climate. The EOS-AM and EOS-PM spacecraft, will work together to observe the daily heating and cooling cycles of the surface and atmosphere. The ALT and CHEM missions are last in the sequence and will provide an important continuation of ocean data which is started in advance of EOS. Moreover, CHEM, at the end of the sequence, can provide an opportunity to fly instruments to study tropospheric chemistry, which are not currently available, as well as an opportunity to monitor the chemistry controlling ozone ten years after UARS.

Models of the climate system should attain the required near-term improvements with observations from the first sequence of EOS spacecraft (EOS-AM, COLOR, EOS-PM, AERO, ALT, and CHEM), and from related ground and aircraft measurements. However, it is important to note that the timescales for processes which govern the climate system of the Earth can extend for several decades. Moreover, to check the accuracy of the models, and to look for changes in the external inputs to the climate system, from human activity and from natural variations, it is important to continue the studies of the components of the climate system. Thus, the sequence of EOS spacecraft is planned to be repeated to provide fifteen year coverage of the climate system.

In summary, models of the climate system of the Earth -- of the atmosphere, the oceans, and the biology -- all need to be improved if we are to determine the extent, causes, and especially the regional consequences of climate change. The EOS-AM and COLOR spacecraft will provide the data need to improve the models of the biology. The EOS-PM and AERO spacecraft will provide the data to improve the models of the dynamics and energy balance of the atmosphere. The EOS-AM and EOS-PM spacecraft will work together to provide data on daily variations of both the surface and the atmosphere. And the ALT and CHEM spacecraft will extend and improve the models of the ocean and atmospheric chemistry.

4. THE IMPACT OF EOS ON ADAPTATION AND MITIGATION STRATEGIES:

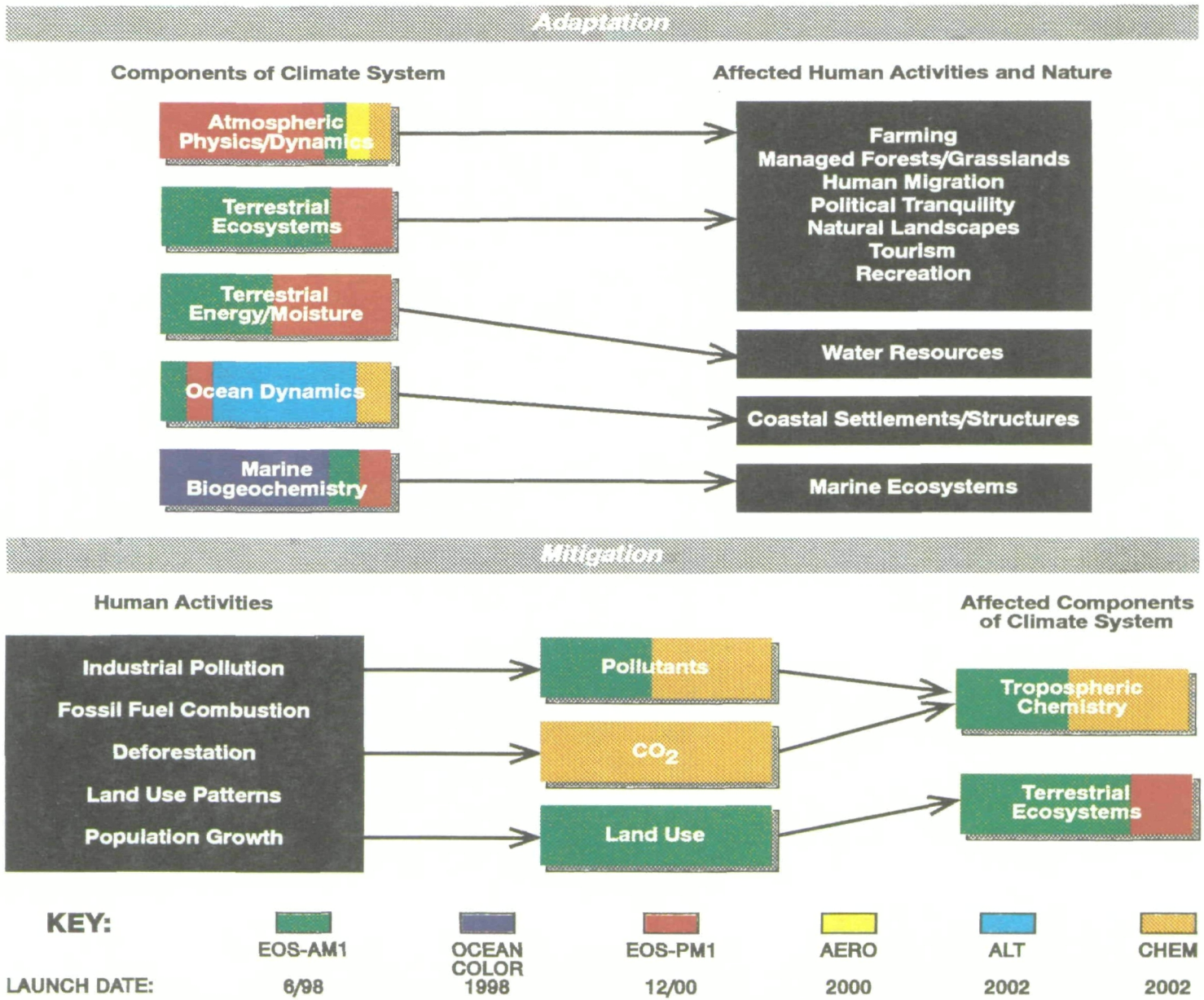
Strategies to deal with climate change fall in two categories: adaptation and mitigation strategies. Adaptation strategies provide options for adjusting human behavior to deal with the impacts of climate change. These strategies come into effect primarily after the climate change has occurred. Mitigation strategies provide options for avoiding the impacts of human activity on the climate. They come into effect prior to the full onset of the climate change and can slow its pace.

Observations from the EOS spacecraft, and from related ground-based studies, will provide the scientific underpinning for adaptation and mitigation strategies in two ways:

> First, individual EOS spacecraft will monitor (i) changes in the components of the climate system to which we may have to adapt, and (ii) the inputs of human activity into the climate system, which we may have to mitigate.
>
> Second, the entire suite of EOS spacecraft, the data they will produce, and the models that will result (See Section 3) will determine (i) the future behavior of the components of the climate system that affect human activity, thereby providing the basis for comprehensive adaptation strategies; and (ii) the impact of individual aspects of human behavior on the entire climate system, thereby providing the basis for comprehensive mitigation strategies.

Consider first the components of the climate system which may change, requiring our adaptation. As can be seen by the arrows in Figure 2, which show the linkages between the components of the climate system, two components have a direct impact on human activity: the Atmospheric Physics/Dynamics component, which describes the actual climate change, and the Terrestrial Ecosystems component. Listed in Figure 3 are aspects of human activity which are sensitive to changes in climate and/or terrestrial ecosystems: farming, managed forests and grasslands, human migration, political tranquility, natural landscapes, and tourism and recreation. In addition, there are components of the climate system which cause secondary changes to which human behavior or nature will be sensitive: changes in the Ocean Dynamics component can affect coastal settlements and structures; the Terrestrial Energy/Moisture component affects water resources; and the Marine Biogeochemistry

Impact of EOS on Adaptation and Mitigation Strategies



component affects marine ecosystems. The list of sensitive aspects of human activity and nature was prepared by the National Research Council study, Policy Implications of Greenhouse Warming.

Individual EOS spacecraft will monitor changes in the components of the climate system that affect human activity. The color coding in Figure 3 is the same as in Figure 2 and illustrates which EOS spacecraft monitors which component. The EOS-AM spacecraft will monitor changes in Terrestrial Ecosystems. The EOS-PM spacecraft, its accompanying small mission AERO, and aspects of the CHEM mission will monitor changes in Atmospheric Physics/Dynamics, and thus the climate. The EOS-AM and EOS-PM spacecraft, which observe the Earth at different times of the day, will work together to provide observations of daily variations on the surface and in the atmosphere, and, in particular, will monitor the Terrestrial Energy/Moisture component. The ALT and CHEM spacecraft will monitor the Ocean Dynamics component, and the COLOR spacecraft, Marine Biogeochemistry.

Monitoring the components of the climate system which affect human activity will provide information on trends and on changes that are of immediate concern. This information by itself, however, will not allow us to determine the future behavior of each of the components of the climate system that affects us, and thus will not permit us to develop long-term plans for how we will adapt to change. Rather, determining the future behavior of components of the climate system requires that we understand the climate system as a whole since the components are coupled together. For example, as is illustrated in Figure 2, the future of the Terrestrial Ecosystems component depends on the behavior of the Global Moisture, Soil, and Tropospheric Chemistry components, and in turn on other components. Predicting the future behavior of each of the components that affect human activity will be done by the entire suite of EOS spacecraft and related ground-based studies, working together to provide the data on which to build the coupled models for biology, oceans and atmosphere of the Earth described in the previous section (Section 3) .

Consider next the human activities that can affect the climate system, which we may chose to mitigate. As illustrated by the arrows in Figure 2, such human activities fall in three categories: the emissions of pollutants into the troposphere or lower atmosphere, e.g. chlorofluorocarbons (CFC's); the emissions of carbon dioxide into the troposphere from the burning of fossil fuels and deforestation; and changes in land use patterns.

Individual EOS spacecraft will monitor the inputs to the climate system from these human activities. As is illustrated by the color-codes in Figure 3, the EOS-AM spacecraft will monitor changes in land use patterns. The CHEM spacecraft will monitor changes in carbon dioxide concentrations . And the combination of CHEM and EOS-AM will monitor the emissions of pollutants into the atmosphere.

Monitoring the inputs of human activity will give us a measure of the magnitude of the influence we are having on the climate system. However, to develop comprehensive mitigation strategies it is necessary to trace the impact of specific human activities

throughout the climate system, determine which are most detrimental, and then consider the economic and social consequences of changing these activities. For example, the emissions of pollutants and carbon dioxide into the atmosphere effects the Tropospheric Chemistry component. In turn, as is illustrated in Figure 2, Tropospheric Chemistry affects Terrestrial Ecosystems and, through a more complicated chain, Atmospheric Physics/Dynamics, both of which impact back on human activities. Tracing the effects of specific human activities throughout the climate system to determine which are most detrimental will be done by the entire suite of EOS spacecraft, their related ground-based studies, and the models of the components of the climate system that will result.

The time scales during which adaptation strategies need to be developed is relatively long; the impact of any potential climate change is not expected for decades. Thus, the full EOS system of spacecraft and related ground-based studies can be the principal source of data on changes on the Earth for developing adaptation strategies. In contrast, the time scale for developing mitigation strategies needs to be shorter if we are to avoid detrimental impacts of climate change. Here, we are in the position of having to develop knowledge of the climate system and mitigation strategies concurrently throughout the Mission to Planet Earth. There are prudent, economically-sound steps that can be taken today, in the absence of certain knowledge of climate change, to serve as an "insurance" policy against unwelcome changes. The early missions of the Mission to Planet Earth program will reveal additional steps that should be taken. Knowledge of the climate system sufficient to develop comprehensive mitigation strategies will be determined by the full observations of EOS, the related ground-based studies, and the models they generate.

5. EOS DATA AND INFORMATION SYSTEM (EOSDIS): EOSDIS is designed to serve the needs of the entire Mission to Planet Earth program. It will improve, archive, and distribute data from the missions that fly in advance of EOS. It will process, archive and distribute data from, and will control the EOS spacecraft.

EOSDIS is designed to be an evolutionary system. It is to be developed with an open architecture, which will allow the easy insertion of new technology that comes on the market, either software or hardware, and will enable the system to respond to changing user requirements. Indeed, the management approach for EOSDIS is to (i) build the system in increments, (ii) try each increment out on the users, and (iii) make appropriate adjustments at each stage. This approach will require a highly interactive arrangement with the contractor who will develop the core of the EOSDIS system. The contractor will be tasked to perform prototyping activities, develop the system in successive versions, each version responding to the lessons of the previous version, and make appropriate modifications to respond to changing user needs. EOSDIS is unprecedented in scope and accessibility. It is larger and more comprehensive than any previous civilian system; it is more interactive than any other large data system. We need to learn as we develop EOSDIS, so that the final system that results is truly responsive to the needs of all the users of EOS data.

The first major activity in EOSDIS, known as Version 0, is to develop an experience base for handling large Earth science data sets by reworking existing data sets into more user-friendly formats. This effort, of course, has the added advantage that it will take existing data sets that have been underutilized and ensure that the information they contain on key issues of global change is more widely available to researchers. Examples of data sets that are being reworked as part of Version 0 include: Advanced Very High Resolution Radiometer measurements of sea surface temperature and vegetation from the NOAA polar orbiting satellites, Special Sensor Microwave/Imager measurements of water vapor and precipitation from the Defense Meteorological Satellites, and Multispectral Scanner land cover data from Landsat.

The subsequent development of EOSDIS will be phased to meet the requirements of missions that are to fly in advance of EOS, and then of EOS itself. For example, the required computing capability and institutional support will be brought on-line only as is needed to handle the data. Thus, the restructuring of EOS, which results in delays in some of the observations from what was expected in the original program (e.g. the flight of EOS-PM occurs later than the original large platform), permits the EOSDIS that will be required by the year 2000 to be smaller than initially envisioned. This adjustment can be made without altering the basic architecture, or the evolutionary design of EOSDIS. However, the budgets for EOSDIS have been reduced substantially, and scale approximately with the reduced cost of the space hardware for EOS.

To validate the approach that is being pursued for EOSDIS, NASA has requested that the National Research Council convene a panel of experts to review our plans, including the validation of its engineering and technical underpinning, and to assess whether current plans provide sufficient resiliency to be adaptable to changing requirements. The report is due in the summer of 1992.

The EOS data will be processed, archived and distributed through Distributed Active Archive Centers, or DAAC's, which are located at major research centers around the country. The DAAC's and their data holdings will be:

Goddard Space Flight Center (Greenbelt, MD.)- Climate Change, Atmospheric Chemistry, and Biogeochemistry.

EROS Data Center (Sioux Fall, SD) - Land Surfaces.

Jet Propulsion Laboratory (Pasadena, CA.) - Physical Oceanography.

Langley Research Center (Hampton, VA) - Radiation Budget, Clouds and Aerosols and Tropospheric Chemistry.

Marshall Space Flight Center(Huntsville, AL.) - Hydrological Cycle and Hydrodynamics.

National Snow and Ice Data Center(Boulder, CO.) - Cryosphere.

Alaska SAR Facility (Fairbanks, AK.) - Sea Ice, Polar Processes Imagery.

Each of these DAAC's has tasks to perform in the Version 0 effort and will receive a small amount of institutional support to do so. However, the DAAC's will be activated to process EOS data only as needed. The EOS-AM spacecraft data will be processed at the DAAC's at the Goddard Space Flight Center, the EROS Data Center, and the Langley Research Center. Thus, these DAAC's will be equipped with the appropriate computer facilities and staffing levels in advance of the launch of EOS-AM. The remaining DAAC's will be equipped later, in time to process the data sets for which they are primarily responsible.

In addition, the EOS data system includes affiliated DAAC's which are designed to serve the needs of specific research and policy-making communities. The most significant affiliated DAAC is the Consortium for International Earth Science Information Network (CIESIN), located in Michigan, which has the responsibility to use the EOS data products to support socioeconomic studies of the human dimension of global change. CIESIN will also serve as the interface with the non-traditional user community such as educators and policy makers.

Additional DAAC's may also be established to take advantage of unique research capabilities at national laboratories. The EOS data system and its DAAC's are expected to serve a worldwide user community that could approach 10,000 scientists.

The EOS data will be acquired through the TDRSS satellite network, and transmitted to the ground through the White Sands, NM ground station. The data will then be transmitted to the NASA facility in Fairmont, WV., where it will be archived in raw form and distributed to the DAAC's for processing and archiving of the data products. The Fairmont facility will also coordinate the Independent Verification and Validation (IV&V) of the EOS data system. Data for potential future operational instruments will also be directly downlinked to operational ground receiving terminals.

6. INTERDISCIPLINARY INVESTIGATIONS: As part of the EOS program, NASA has established 29 Interdisciplinary Teams, whose job it is to develop a quantitative understanding of the processes which govern the climate system of the Earth, and to incorporate this knowledge into predictive models which can serve as the basis for policy decisions. These Interdisciplinary Teams are being established at 12 US universities, 7 NASA facilities, and 9 international research facilities and universities.

7. MISSIONS IN ADVANCE OF EOS: In advance of EOS some 16 free-flying satellites will be launched to make observations of global change on the Earth. These missions are to be conducted by the US and our international partners. In addition, three major Space Lab series will be launched on the Space Shuttle to study global change, and there will be continuous, routine observations from the NOAA and military weather satellites. This extensive period of observations is known as Phase 1 of the Mission to

Planet Earth.

It is important to note that all of the instruments that will fly on the EOS spacecraft have less capable versions, and in some cases identical versions, that will fly on these Phase 1 missions. Thus, Mission to Planet Earth is an evolutionary program. It is providing important information on global change today, will provide more such information throughout Phase 1, and will evolve into more comprehensive and detailed observations when the EOS spacecraft fly.

8. THE ROLE OF THE DEPARTMENTS OF ENERGY(DOE) AND DEFENSE (DOD): As noted by the Frieman Committee, the DOE and DOD can make important contributions to the Mission to Planet Earth. In particular, the DOE may be able to provide additional spacecraft to Phase 1 of the Mission to Planet Earth. Although there are a large number of missions that fly during Phase 1, several review committees have noted that there is a discontinuity in Earth radiation budget observations, between NASA's measurements on the ERBS and NOAA 9/10 spacecraft, and NASA's measurements on the US/Japan TRMM mission and subsequent EOS spacecraft. The DOE is considering providing one or more small spacecraft which can provide these observations. To be useful the observations must commence no later than 1995, since TRMM flies in 1997, and their calibration must be well understood to help provide continuity between the earlier and future observations.

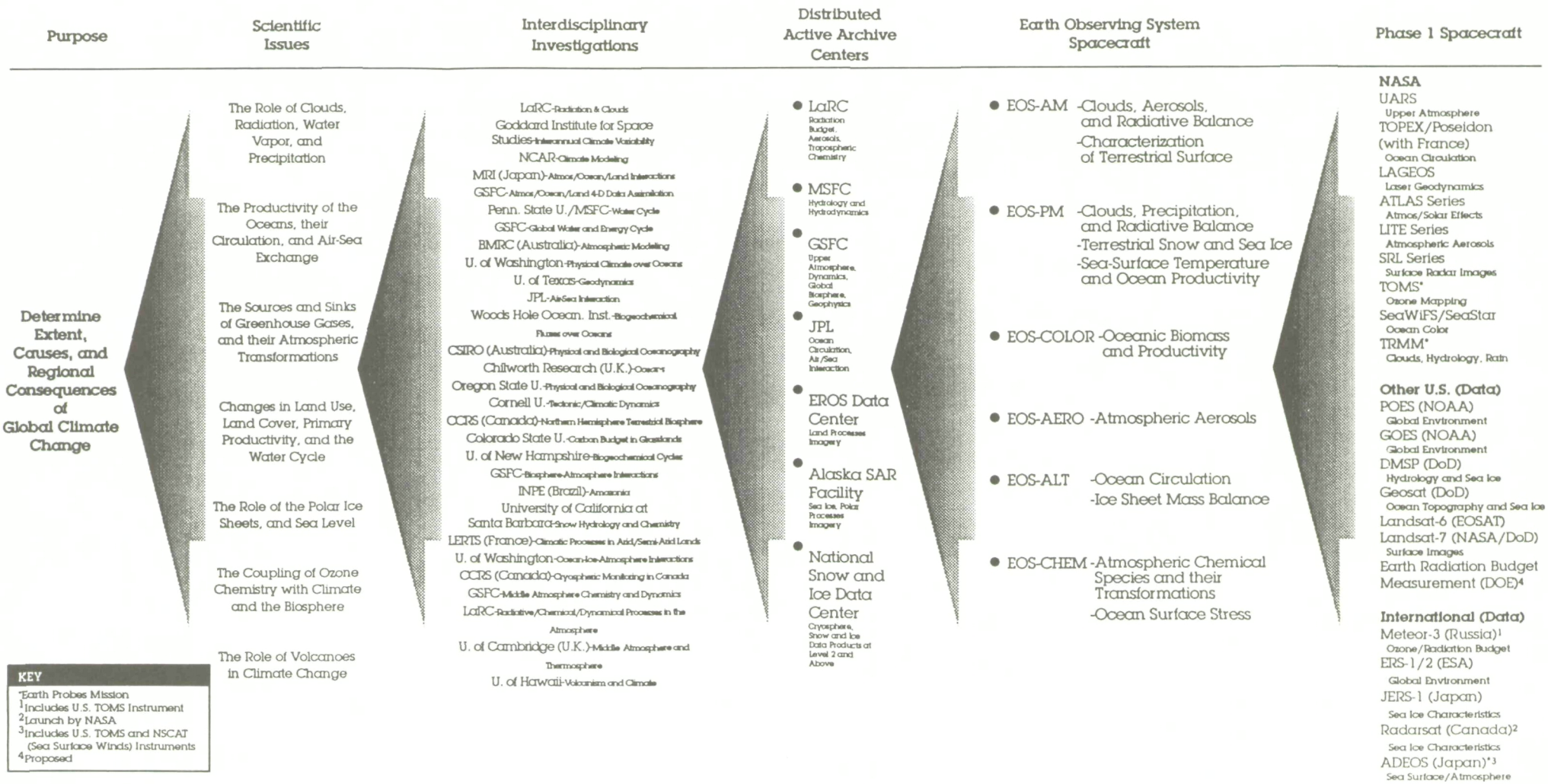
Further, the DOE and DOD may be able to assist in the development of new technologies for use in subsequent generations of EOS instruments. The restructured EOS does not include a Laser Atmospheric Wind Sounder, an advanced Synthetic Aperture Radar, or a light-weight, high-resolution imaging spectrometer. These instruments will be important for future global change studies. It would be very helpful for DOE and DOD to execute technology demonstration projects that would lead to reliable, more compact, and less expensive versions of these and other advanced instruments.

9. SUMMARY OF THE MISSION TO PLANET EARTH: The structure of the Mission to Planet Earth -- the Phase 1 missions, the EOS spacecraft, the DAAC's, the interdisciplinary investigations, and the science and policy objectives -- is illustrated in Figure 4, and summarized as follows:

1. During Phase 1 of Mission to Planet Earth, which begins now and continues through 1998, a large number of satellites will be launched by NASA, other Federal Agencies, and our international partners to monitor the climate and study specific processes which may control its evolution.

2. Beginning in 1998, the Phase 1 satellites will be replaced by a constellation of intermediate and small satellites as part of the Earth Observing System, or EOS. The instruments on the EOS spacecraft are more capable and can provide more comprehensive long-term observations than those from the Phase 1 spacecraft.

Mission to Planet Earth



KEY

*Earth Probes Mission
[1]Includes U.S. TOMS Instrument
[2]Launch by NASA
[3]Includes U.S. TOMS and NSCAT (Sea Surface Winds) Instruments
[4]Proposed

3. All of the data on the interactions and processes which control the climate will be processed and archived in Distributed Active Archive Centers, or DAAC's.

4. The data in the DAAC's will be made readily available to all researchers who study global change. In particular, it will be the the basis for studies by the Interdisciplinary Teams that NASA has established.

5. These Interdisciplinary Teams, along with other researchers, are charged with developing a quantitative understanding of the seven key science issues (listed in section 2) and incorporating this knowledge into predictive models that will determine the extent, causes, and regional consequences of global climate change.

10. FUNDING REQUIREMENTS: The President's budget estimates for fiscal year 1994 through 1997 reflect a government-wide policy to present a nominal freeze in budget authority in all outyears for domestic discretionary spending programs. This serves to emphasize that in FY 1994 and subsequent years, each proposal for increased funding will have to compete "on its merits" against all other domestic discretionary programs, and decisions made accordingly within the caps and overall fiscal constraints. The outyear funding estimates shown in this report represent preliminary program planning estimates that reflect a continuation and extension of the programs proposed in the FY 1993 budget. These programs may not be funded at these levels, however, given competition with other priorities and fiscal constraints. Each program will compete each year on the merits.

The restructured EOS program, including the spacecraft (EOS-AM, EOS-PM, COLOR, ALT, and CHEM), EOSDIS, and the supporting science has been designed to accommodate the $11 billion funding cap through FY 2000, as directed by Congress. Indeed, the design philosophy has been: First, to eliminate all instruments that are not essential to study global climate change. Second, to insure that there is no unnecessary duplication of observations with international missions studying global climate change. Third, to provide an adequate data and information system, and supporting science. Fourth, to launch the first EOS spacecraft, EOS-AM, as early as is programmatically feasible. And fifth, to launch all other EOS spacecraft as early as permitted by the funding profile associated with the $11 billion cap.

The EOS program has four basic components: the space hardware -- spacecraft and instruments, the EOSDIS data system, the supporting science, and mission operations. The funding profiles for each component, through FY 2000, is shown in Figure 5. The profiles total to $11 billion. The profiles have relatively modest growth from FY 1992 to FY 1993, in compliance with Congressional direction, and then increase substantially from FY 1994 to FY 1995. The funding profiles level, increasing only at the rate of inflation after FY 1997. This level funding profile is assumed to

continue after FY 2000 to complete the development of the ALT and CHEM spacecraft, to continue, through repeated launches of EOS spacecraft, the long-term monitoring of the climate, and to continue data reduction, distribution, and analysis.

The total cost of the space hardware component, through FY 2000, is approximately $6 billion. The ground segment -- EOSDIS and science -- totals to $5 billion. This proportion of ground to flight segments is very high by the standards of any previous NASA program. It reflects the strong commitment of NASA to use EOSDIS to improve, archive and distribute the data from spacecraft in Phase 1 of the Mission to Planet Earth, thereby substantially increasing the understanding of global change that will result from these missions. Developing an operational EOSDIS in advance of the launch of the EOS-AM spacecraft will also insure the immediate return of useful information from all the EOS spacecraft. After FY 2000, the proportion of ground to space segments increases; by end of the full 15-year operational life of EOS, the total cost of the ground segment will be approximately 60% of the overall mission cost.

The space hardware costs are broken out by individual spacecraft mission (e.g. EOS-AM, EOS-PM, etc.) in Figure 6. The cost estimates used for the instruments that were to have flown on the original large EOS platform and the EOS-AM spacecraft bus are well understood since both elements are under contract (although the spacecraft contract will be modified to reflect the current downsized configuration). Cost estimates for subsequent spacecraft and for the instruments that are not currently under development are preliminary, based on derivation from the current EOS-AM definition and development estimates and analogy with previous flight project experience. These estimates will be updated before beginning development of these spacecraft and instruments.

Most of the space hardware costs in FY 1993 and FY 1994 are associated with development of the EOS-AM spacecraft and instruments, and the beginning of the development of EOS-PM. The growth in the budget in FY 1995 is essential to maintain the schedule of EOS-AM and EOS-PM and to begin the full development of AERO, CHEM, and ALT. It should be noted that the small COLOR mission is not shown in this figure. NASA assumes that it can acquire the data from COLOR as a data purchase only, in the same manner as it is acquiring the data from the SeaStar mission that will fly during Phase 1. Accordingly, the costs for COLOR are bookkept in EOSDIS. The category called "Other" in the figure includes the costs of a copy of the CERES instrument which is to fly on the US/Japan TRMM mission in 1997 and begin measurements of the Earth's radiation budget prior to EOS. The "Other" category also includes a wedge to fund additional instruments for flights of opportunity, such as to provide measurements of solar luminosity, or to study other aspects of global change that may become important in the coming years.

Some cost comparisons are instructive. The spacecraft for Phase 1 of the Mission to Planet Earth, which are listed in Figure 3 in Section 8, have development costs that total to nearly $8 billion, as compared to the $6 billion cost for EOS. The cost for Phase 1 missions is split among NASA - $2.1 billion, the European Space Agency -

$1.1 billion, Japan - $1.8 billion, Canada - $0.35, and NOAA/DOD/DOE - $2.5 billion. (Costs for European, Japanese and Canadian missions are estimates only).

The costs for the science portion of EOS are shown in Figure 7. Included here are the costs for the Interdisciplinary Teams, the costs for scientists to develop the algorithms to process EOS data, and the costs for both of their computer facilities. In the NASA budget, the costs for personnel and computer facilities to do algorithm development are bookkept with the costs for the spacecraft for which the algorithms will be developed. NASA is committed to having the algorithms for each EOS spacecraft fully developed prior to its launch, so that there will be no delay in the use of the data. The costs for algorithm development thus increase beginning in FY 1995, in preparation for the EOS-AM launch.

Figure 8 illustrates the costs associated with EOSDIS. Funds for Version 0 support NASA's efforts to take existing Earth science data sets and make them more available and useful to researchers. This effort will both improve our understanding of global change and provide an experience base on which to develop the full EOSDIS. Each of the DAAC's will participate in Version 0 and is provided a small level of institutional support to do so. Funds for Version 1, etc. support the establishment of the EOSDIS capability -- its basic architecture and associated networking. As in the case of algorithm development, NASA is committed to have the appropriate level of EOSDIS capability on line prior to the launch of EOS-AM. Funding is also provided for the Independent Verification and Validation activities and the in-house support for managing the data system at the Goddard Space Flight Center. Finally, funding is provided to establish the data processing capability at selected DAAC's, as is needed. The first DAAC's to be brought on line to process EOS-AM data are the Goddard Space Flight Center, the EROS Data Center, and the Langley Research Center. The remaining DAAC's will be activated as they are needed to process data from subsequent EOS spacecraft.

Cost comparisons with the original EOS program are difficult since the restructuring has been such a fundamental change. It is interesting to note, however, that to fly most of the instruments on the original large platform now requires three spacecraft -- EOS-AM, EOS-PM, and CHEM -- in the restructured program. The total cost of these three intermediate satellites is of course larger than the cost of the original large platform, in part because the program is spread over more years and paid for now in inflated dollars, and in part because the economy of scale of the large platform is lost. However, as can be seen in Figure 9, if we compare the cost profile required to launch the large platform and its instruments in late 1998 with the cost profile available for EOS-AM, EOS-PM, and CHEM, we see that the large platform required substantially more up-front funding. Equivalently, with limited funds available in FY 1993 and FY 1994, the large platform could not be launched until the year 2000, or later. The multiple platform approach has the clear advantage that it can begin the crucial EOS measurements early, with EOS-AM in June 1998, with only a modest growth in funds required in the early years.

EARTH OBSERVING SYSTEM
RESTRUCTURED PROGRAM

SUMMARY

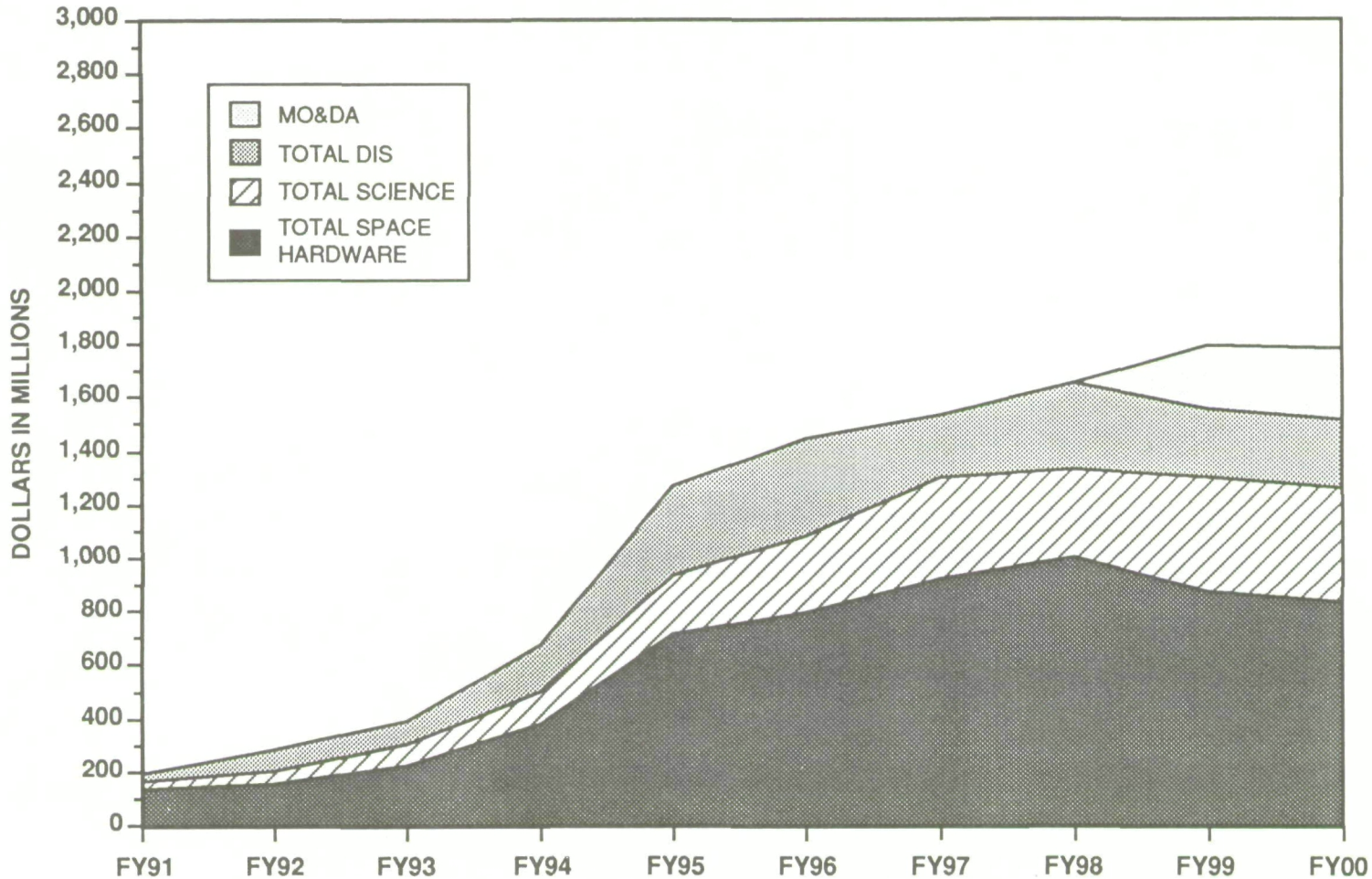


Figure 5

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EARTH OBSERVING SYSTEM
RESTRUCTURED PROGRAM

SPACE HARDWARE SUMMARY

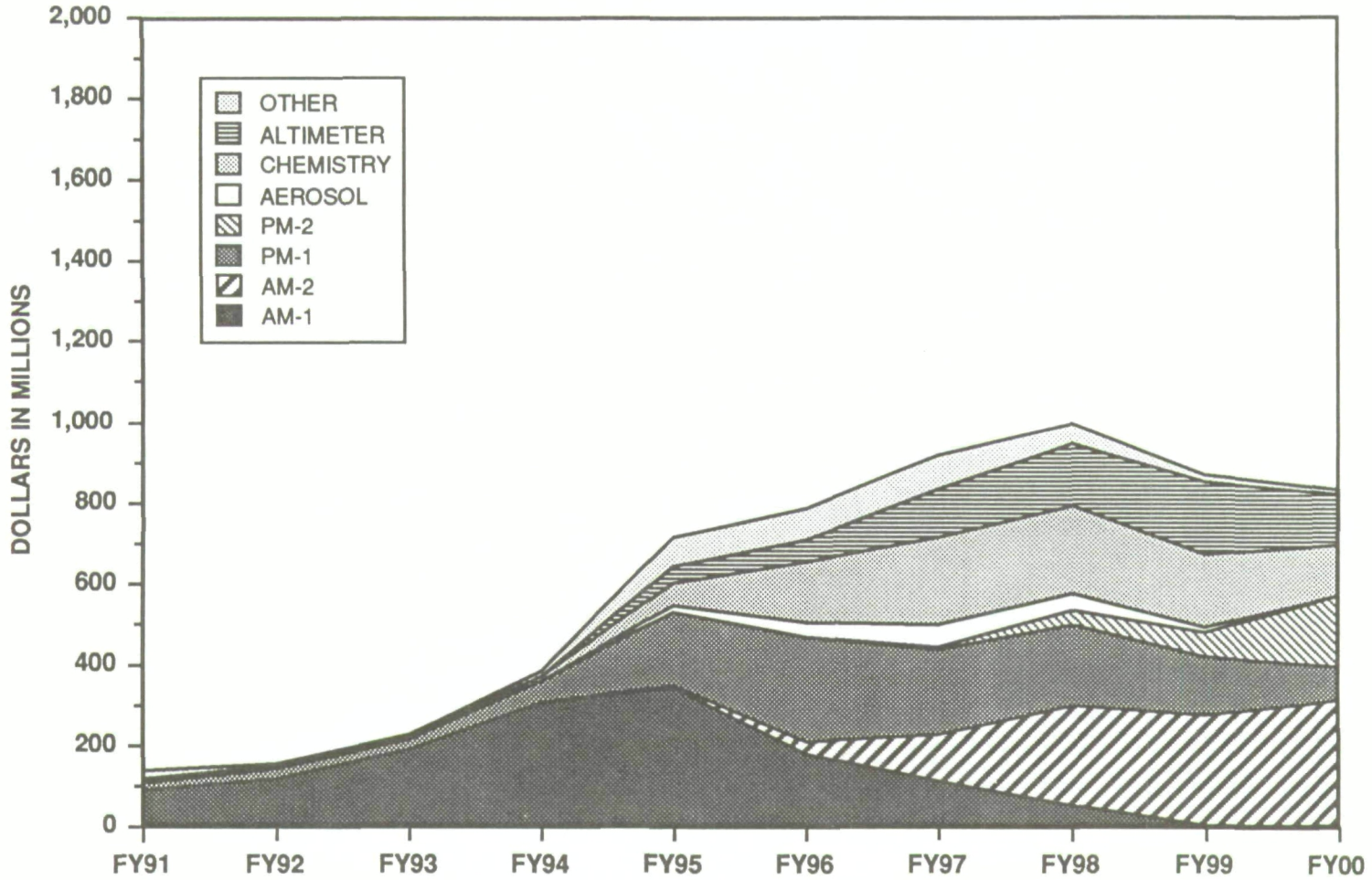


Figure 6

SP-068-15d
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EARTH OBSERVING SYSTEM
RESTRUCTURED PROGRAM

SCIENCE

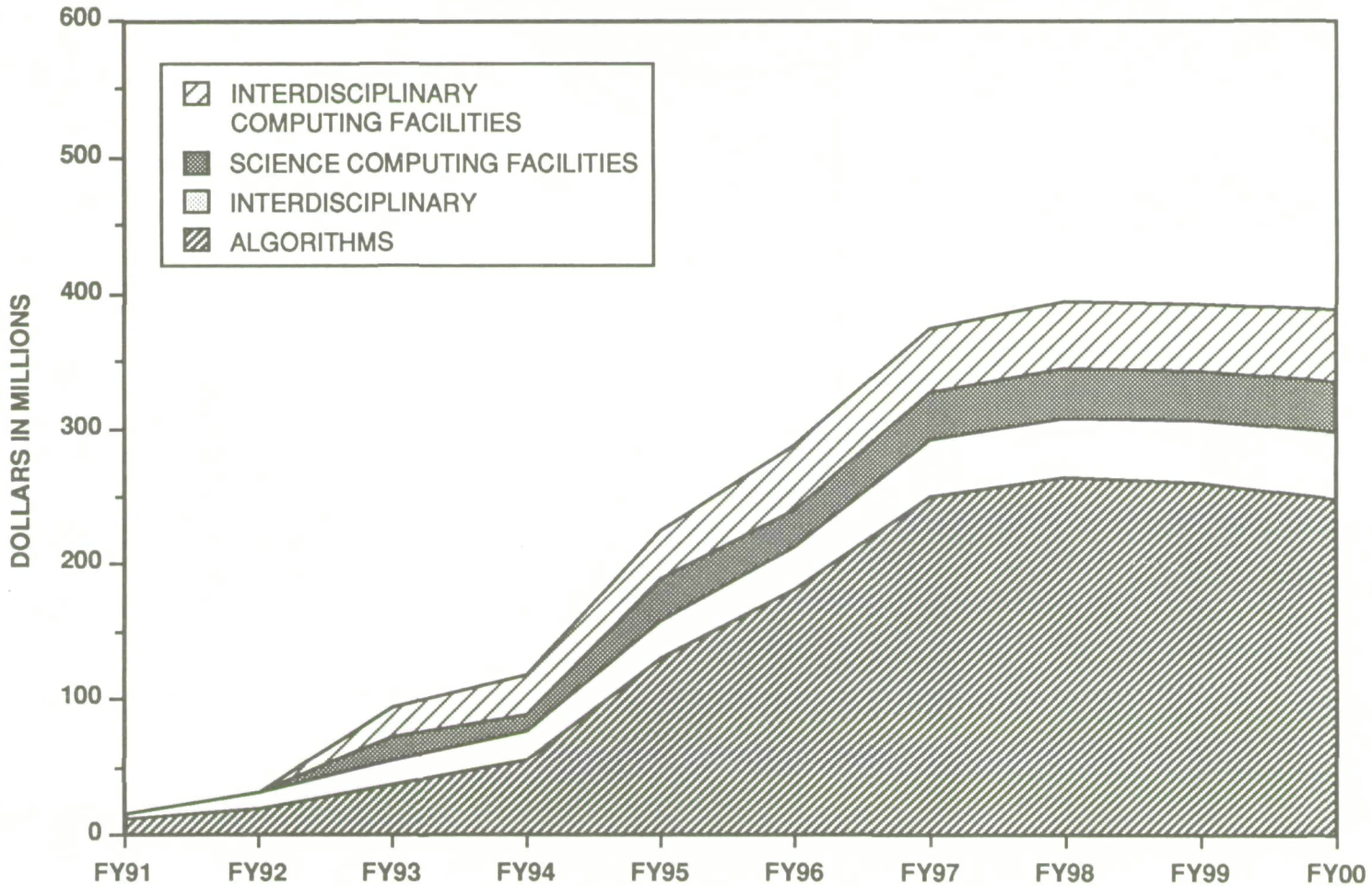


Figure 7

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EARTH OBSERVING SYSTEM
RESTRUCTURED PROGRAM

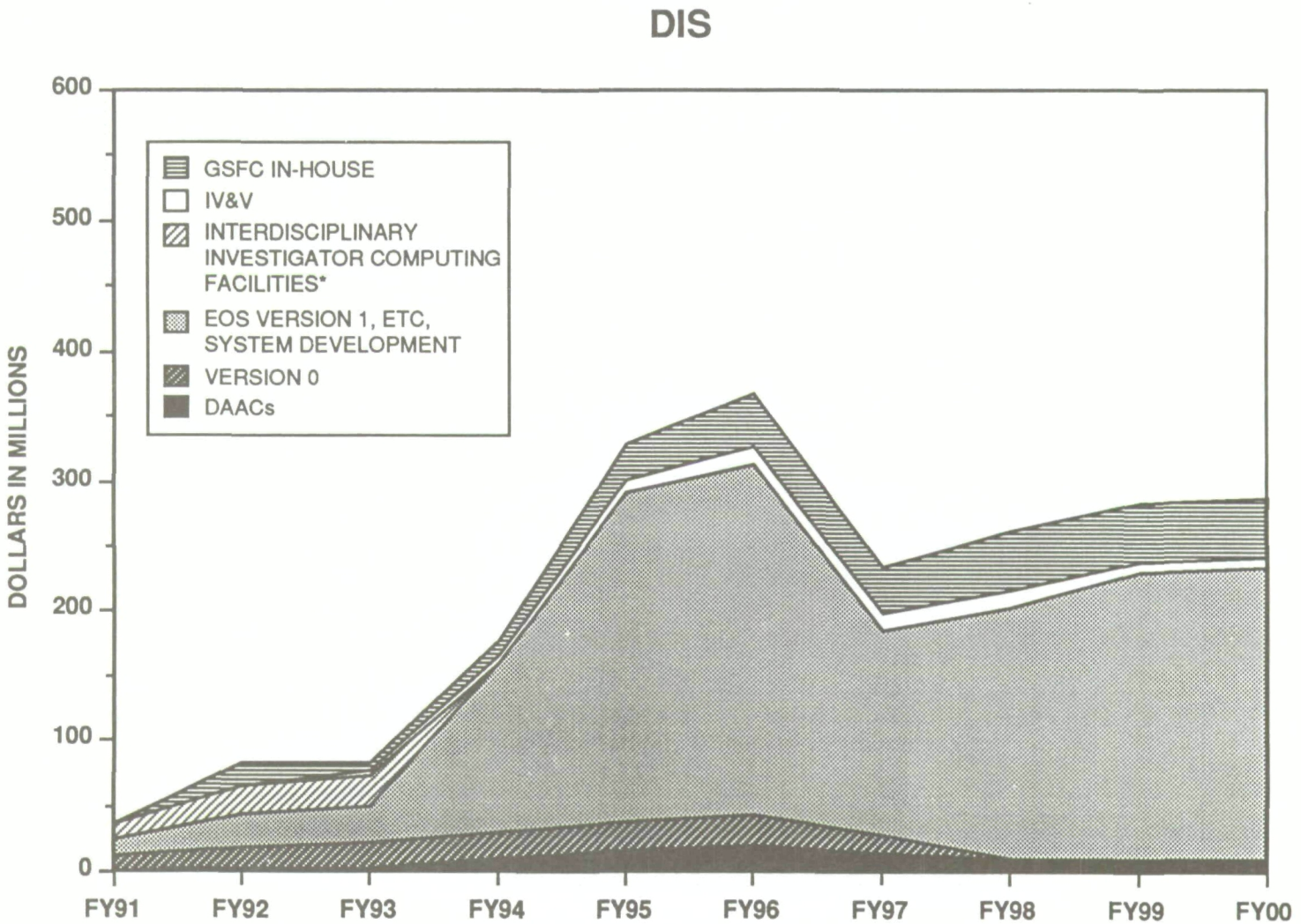


Figure 8

* Beginning in 1994 IICFs will be Included in Science

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EARTH OBSERVING SYSTEM
RESTRUCTURED PROGRAM

EOS SPACECRAFT COMPARISON

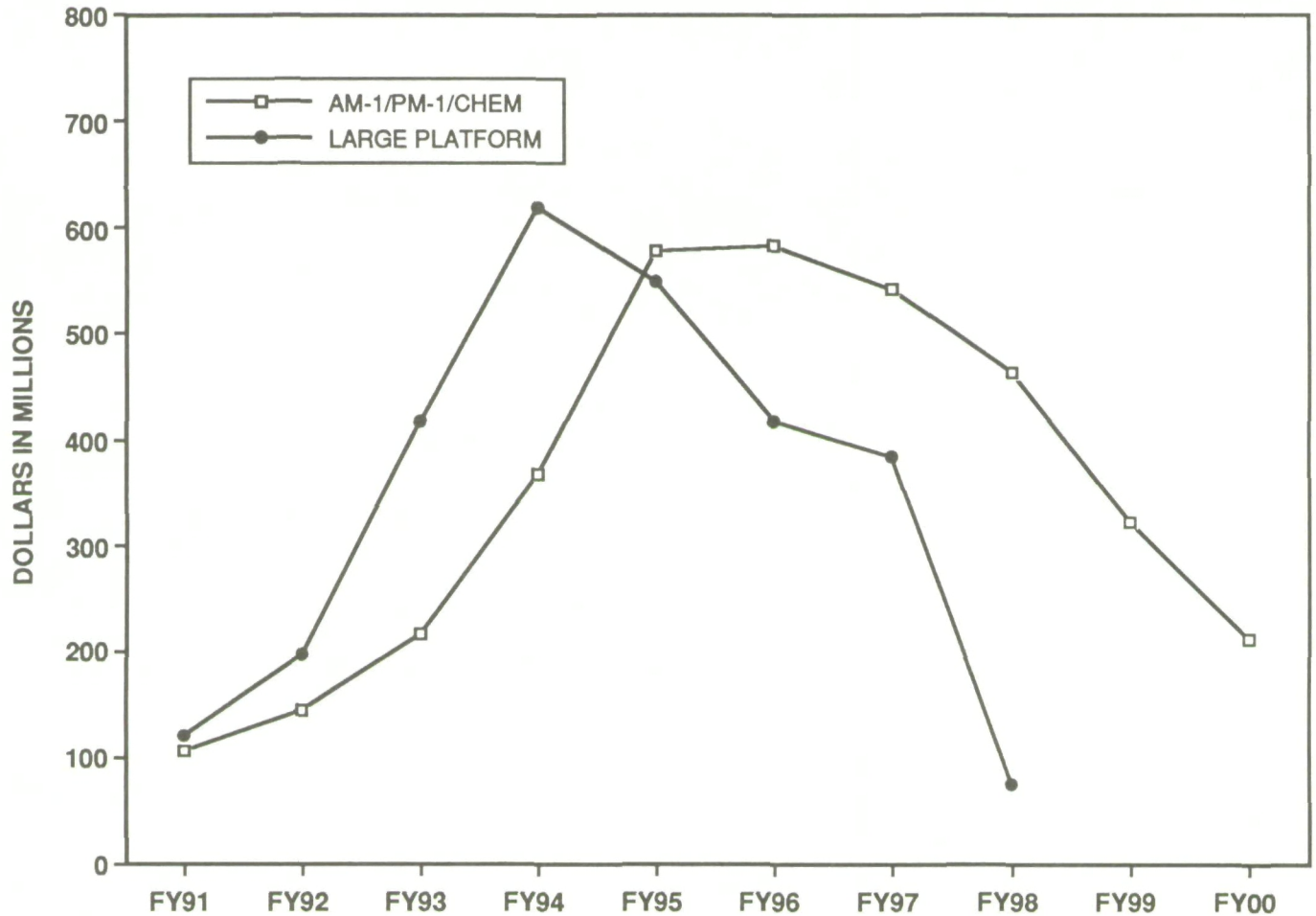


Figure 9

DATE DUE

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Report to Congress on the
restructuring of the earth

NASA HEADQUARTERS
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